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PROPOSAL FOR A BROADBAND HIGHER-ORDER-MODES SUPPRESSOR FOR RADIOFREQUENCY ACCELERATING CAVITIES

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An important task in the design of the radiofrequency cavities for the ELETTRA Synchrotron Light Source is to provide adequate damping for the higher-order modes (HOM) that could be excited in the cavity by the electron beam. In order to satisfy this request, we decided to develop a broad-band suppressor, which can be used instead of a number of couplers, each tuned at a dangerous cavity mode frequency. A prototype of a waveguide suppressor directly coupled to a cavity has been produced and tested. The measurements on this device show that a large number of HOMs are practically eliminated. A few modes do not disappear, but they are heavily damped. The damping effect on the fundamental mode of the cavity is small and is thus acceptable.

1 INTRODUCTION

The HOMs of an accelerating cavity require adequate damping in order to avoid multibunch instabilities. Usually during the design one can foresee[1,2] and theoretically try to displace the modes that strongly couple to the beam and hence are excited; when the cavity is operating, the most dangerous modes can be damped by means of dedicated suppressors[3–7].

Anyway, an optimum solution should point toward a coupler with broadband characteristics, able to suppress as many modes as possible without affecting the fundamental mode; in the optimal case the device should have the characteristics of a high-pass filter. Waveguides make simple high-pass filters with sharp cutoff characterstics. Therefore, the leading idea for a wide band suppressor is to couple a suitable waveguide to the resonant cavity.

The analytical computation of the behavior of such a structure is difficult and requires much computer time, so in order to evaluate the effectiveness of this suppressor as quickly as possible, a prototype, made of a waveguide coupled to a pill-box cavity expressly designed for the purpose, has been built.

The design of the broad-band suppressor developed at the laboratories of Sincrotone Trieste and the measurements carried out on it are described below.

2 OPERATING PRINCIPLE

It is well known that waveguides have an infinite number of propagating modes. Each mode can propagate when it is excited at frequencies above its cutoff frequency; the mode with the lowest cutoff frequency for the particular waveguide is the fundamental (also called dominant) one. This is normally the operating mode.

In our case, the cavity, driven by the beam, becomes the exciting source for a waveguide coupled to it and for each cavity mode that is coupled to a propagating mode of the waveguide. If the waveguide is terminated on a matched load, the cavity mode is consequently damped. It is clear that the mechanical coupling between cavity and waveguide influences the damping ratio of each mode; hence, the waveguide should be coupled to the cavity by an aperature of optimized shape and size.

The damping effect on the fundamental mode of the cavity should be very small. Therefore the cutoff frequency of the dominant mode of the waveguide, f_c, must be chosen above the resonant frequency of the operating mode, f_0. From the waveguide theory it follows that if $f_0 < 0.9f_c$ a reasonable safety margin is guaranteed. On the other hand the first higher mode should be allowed to propagate to the load. Good propagation in the waveguide is guaranteed if the condition $f_{01} > 1.2f_c$ is fulfilled. These two conditions give the design specification for the size of the waveguide.

The quite satisfactory results obtained on an S-band model have led us to go on with a prototype at the working rf frequency of the machine.

3 DESIGN OF THE PILL-BOX CAVITY AND MEASUREMENTS

A brass pill-box cavity has been built in order to test the waveguide suppressor. The mode spectrum of this cavity should be similar to that of the Elettra cavities. With this goal, the diameter and the height of the pill-box cavity were chosen as

$$D = 460 \text{ mm},$$
$$h = 187 \text{ mm}.$$

Table 1 lists the first six zero and dipole modes of the pill-box cavity and compares them with the first six zero and dipole modes of the Elettra cavity. Zero modes are modes without azimuthal variations. They are characterized by $m = 0$, where m is the first index in the code TX_{mnr} for the modes of a resonant cavity. Dipole modes have one azimuthal variation and are characterized by $m = 1$. The mode spectrum of the pill-box cavity has been measured up to 2 GHz. The measured resonance frequencies and *unloaded* quality factors are shown in Table 2. The analytical values are not shown in Table 2 since the measured values agree very well with the predicted ones. A graphical representation of the measured spectrum is shown in Figure 1.

TABLE 1
Comparison between the first six zero ($m = 0$) and dipole ($m = 1$) modes of the pill-box cavity (analytical computation of frequencies) and of the Elettra cavity (frequencies computed with the code OSCAR2D for $m = 0$ and with the code URMEL-T for $m = 1$).

m	Pill-Box Cavity Frequency (MHz)	ELETTRA Cavity Frequency (MHz)
0	499	500
1	795	748
1	888	751
0	945	945
1	1130	1120
0	1150	1061

4 SUPPRESSOR DESIGN; FIRST PROTOTYPE AND MEASUREMENTS

As a first step we use a rectangular waveguide. The cutoff frequency f_c for the TE_{10} waveguide mode depends on the longer dimensions of the rectangular cross section, a; this frequency must fit the conditions described in Section 2. With the frequencies measured on the pill-box cavity (see Table 2) these conditions become

$$497\,\text{MHz} < 0.9 f_c \quad \text{and}$$
$$795\,\text{MHz} > 1.2 f_c$$

The choice

$$f_c = 600\ \text{MHz}$$

TABLE 2
Measured mode spectrum of the pill-box cavity (zero and dipole modes).

Order	Mode	Frequency, MHz	Q_U
1	TM_{010}	497	15 000
2	TM_{110}	795	18 500
3	TE_{111}	901	16 500
4	TM_{011}	950	13 000
5	TM_{111}	1136	13 500
6	TE_{011}	1146	22 000
7	TM_{020}	1146	22 500
8	TE_{121}	1376	35 000
9	TM_{012}	1406	15 500
10	TM_{120}	1457	25 000
11	TE_{112}	1670	17 000
12	TM_{121}	1675	20 000
13	TM_{021}	1695	17 000
14	TM_{030}	1798	28 000
15	TM_{112}	1810	18 500
16	TE_{012}	1817	27 000
17	TM_{031}	1974	18 500

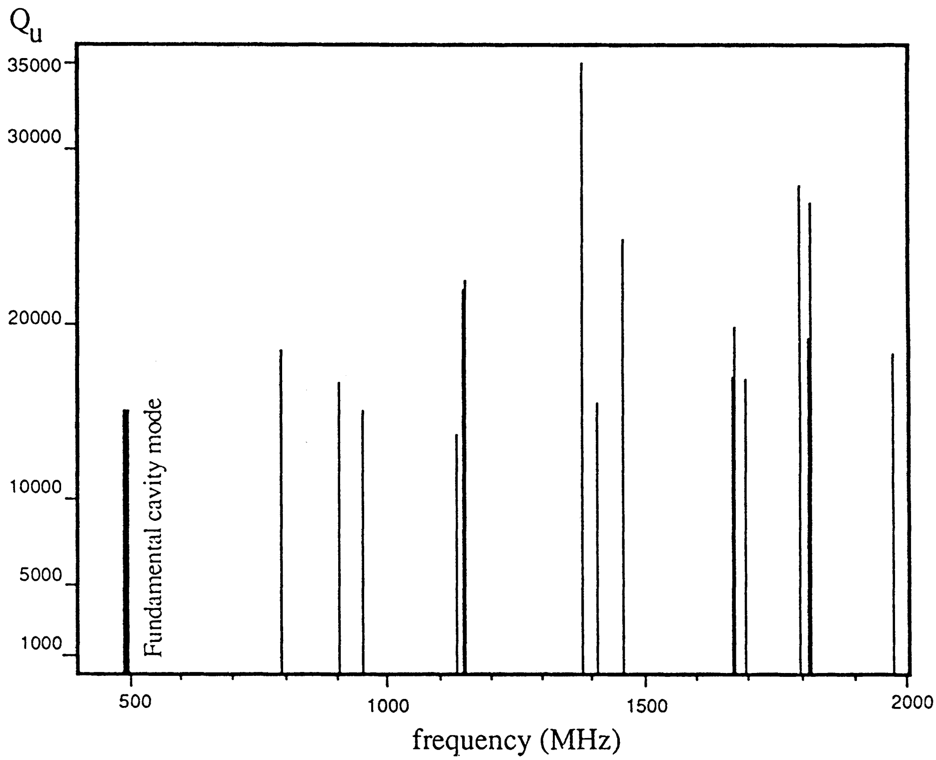

FIGURE 1 Mode spectrum of the undamped pill-box cavity.

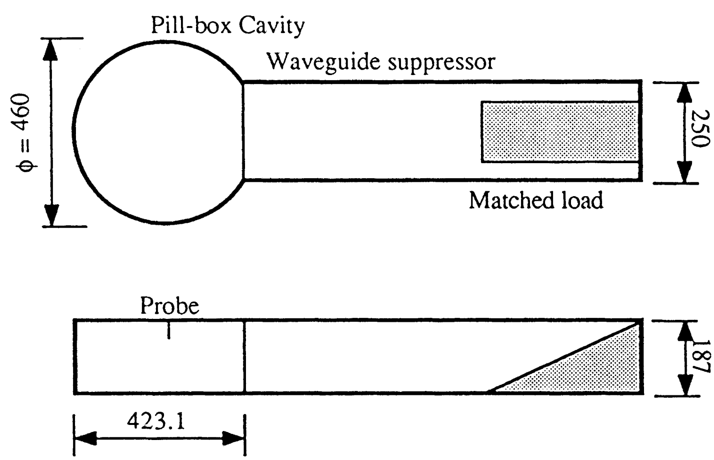

FIGURE 2 Sketch of the pill-box cavity coupled to the waveguide suppressor (the dimensions shown are those of the prototype *wbs_rf1*). The coupling probe for longitudinal modes is also shown.

TABLE 3
Zero and dipole modes spectrum, measured with the *wbs_rf1* coupled to the cavity (— means that the mode is practically eliminated).

Order	Mode	Frequency (MHz), damped cavity	Q_{U_u}, undamped cavity	Q_{U_d} $\varphi = 0°$ damped cavity	Q_{U_d} $\varphi = 90°$ damped cavity	$\frac{\Delta Q_U}{Q_{U_u}}$ (%)
1	TM_{010}	475	15 000	13 500	13 500	10
2	TM_{110}	793/—	18 500	17 700	—	100
3	TE_{111}	902	16 500	12 500	12 700	23
4	TM_{011}	937	13 000	9700	9700	25
5	TM_{111}	1134	13 500	7600	7000	48
6	TE_{011}	—	22 000	—	—	100
7	TM_{020}	—	22 500	—	—	100
8	TE_{121}	1376	35 000	2500	3500	93
9	TM_{012}	—	15 500	—	—	100
10	TM_{120}	—	25 000	—	—	100
11	TE_{112}	—	17 000	—	—	100
12	TM_{121}	1671/1672	20 000	3600	7000	82
13	TM_{021}	1686	17 000	4800	4800	72
14	TM_{030}	1777	28 000	10 500	10 500	63
15	TM_{112}	1808/—	18 500	8600	—	100
16	TE_{012}	—	27 000	—	—	100
17	TM_{031}	1954	18 500	3000	3000	84

satisfies both conditions. This cutoff frequency of the waveguide dominant mode TE_{10} requires a waveguide base length

$$a = 250 \text{ mm}.$$

The height of the waveguide, b, in the first prototype, has been chosen equal to the height of the cavity; that is,

$$b = 187 \text{ mm}.$$

The coupling window is a rectangular aperture equal in size to the waveguide section, that is $250 \times 187 \text{ mm}^2$. This is the simplest shape for the window, it could be necessary to optimize the window shape and size in the final design.

The opposite end of the waveguide has been closed with a matched, homemade termination. The complete structure is 1.5 m long; a shorter one can be obtained by minimizing the load length, taking into account that the load should begin beyond 0.6 m from the window—that is, roughly a free-space wavelength at the frequency of the fundamental cavity mode.

This is a rather important point that we like to emphasize. The amplitude of a nonpropagating mode dies out exponentially along the guide and the attenuation depends on the ratio f_c/f, where f_c is the cutoff frequency of the mode. Therefore, even if the cutoff frequency of the waveguide dominant mode is higher (as it must be) than the operating frequency of the cavity, the cavity operating mode penetrates a little into the waveguide. If the waveguide isn't long enough before the load, a large amount of useful power could be dissipated. In our case, at one free-space wavelength the field is attenuated by roughly 99%; thus we are guaranteed that no useful power will be dissipated on the load. Designs for other particular accelerating cavities will demand a different load distance.

A sketch of the complete structure is shown in Figure 2. We will refer to this device as *wbs_rfl*.

After the suppressor has been applied to the cavity the mode spectrum was measured again.

It should be noted that in an accelerating cavity the higher order modes are driven by the beam, while in this simulation they are artificially excited by an external source coupled to the cavity (a probe for longitudinal modes—see Figure 2—and a coupling loop for dipole modes; this loop isn't shown in Figure 2). The simulation is completely acceptable when, as in this case, the gap-transferred impedance of the cavity coupling system is very high.

The results of the measurements are shown in Table 3.

The graphical representation of the damped spectrum can be found in Figure 3; this figure takes into account the values of the last column of the preceding table.

Referring to Table 3, it should be noted that zero modes have no azimuthal variations; on the contrary, the field components of a dipole mode depend on the

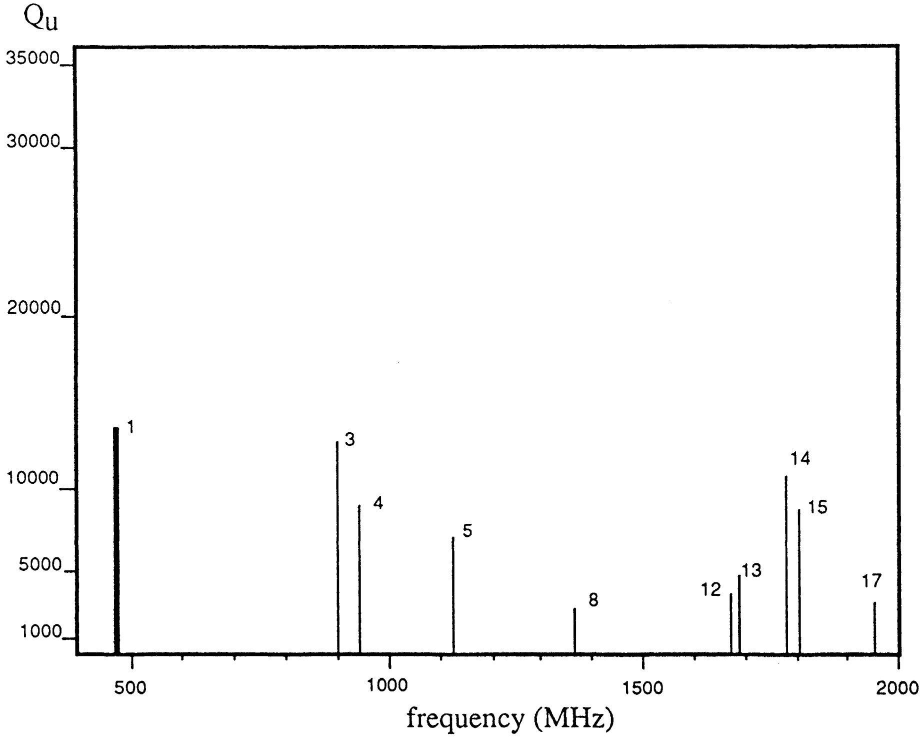

FIGURE 3 Model spectrum of the pill-box cavity coupled to the suppressor prototype *wbs_rf1*.

azimuthal coordinate. Hence, according to the relative position between the dipole mode field pattern and the coupling window (which in our case is determined by the loop position), the damping effect changes. In this way the damping device eliminates 8 modes out of 16.

The Q measured on the cavity with *wbs_rf1* is about 10% less than the undamped value; that is quite acceptable. (The accuracy of the Q measurements is better than 5%).

The best effect on dipole modes should be reached by coupling to the cavity two waveguides shifted by an azimuthal angle of 90°.

5 SECOND MODEL

In spite of the large coupling window we have seen above that some cavity modes remain largely undamped. An investigation of these modes shows that they couple very slightly to the dominant waveguide mode, while, as expected, they can couple strongly to many of the higher modes of the waveguide. Consequently, a more complete damping effect is to be expected if the waveguide can propagate also those modes.

The analysis of the field lines of the modes TE_{111} and TM_{011}, which remain practically undamped with the suppressor *wbs_rf1*, shows a field pattern near the coupling aperture such that these modes couple strongly to the waveguide mode TE_{11}, while they are nearly uncoupled to the dominant TE_{10} waveguide mode.

Now, owing to the fact that the TE_{11} mode has a cutoff frequency of 1.0 GHz in the waveguide *wbs_rf1*, it is clear that the two modes TE_{111} and TM_{011}, both with resonance frequency below 1 GHz, can't propagate to the load and therefore remain undamped.

The cutoff frequency of the TE_{11} mode, which should be reasonably below 900 MHz in order to damp the two considered cavity modes (see Table 3), depends both on the height and on the base lengths of the waveguide section. Since the base length fixes the dominant-mode cutoff frequency, the condition on the TE_{11} cutoff frequency has to be satisfied by an appropriate choice of the height. With $a = 250$ mm, a satisfactory safety margin can be obtained with a square section waveguide, which corresponds to

$$f_c TE_{11} = 850 \text{ MHz}.$$

Thus a new model has been produced, *wbs_rf2*, with section size $a = b = 250$ mm. The coupling window, the waveguide length, and the matched load are the same as before.

The mode spectrum obtained by coupling the pill-box cavity to the model *wbs_rf2* is listed in Table 4 and shown in Figure 4.

These results confirm that, while in the first suppressor some modes didn't propagate to the load, in the second suppressor they are allowed to propagate to the load and are consequently damped. The damping rate for these modes, TE_{111} and TM_{011}, is now very close to 100%.

TABLE 4
Pill-box cavity mode spectrum, with suppressor *wbs_rf2*.

Order	Mode	Frequency (MHz), damped cavity	Q_{U_u}, undamped cavity	Q_{U_d} $\varphi = 0°$ damped cavity	Q_{U_d} $\varphi = 90°$ damped cavity	$\frac{\Delta Q_U}{Q_{U_u}}$ (%)
1	TM_{010}	473	15 000	13 200	13 200	12
2	TM_{110}	792/—	18 500	17 300	—	100
3	TE_{111}	—	16 500	—	—	100
4	TM_{011}	—	13 000	—	—	100
5	TM_{111}	1132	13 500	4400	3500	74
6	TE_{011}	—	22 000	—	—	100
7	TM_{020}	—	22 500	—	—	100
8	TE_{121}	1375	35 000	6000	6000	83
9	TM_{012}	—	15 500	—	—	100
10	TM_{120}	—	25 000	—	—	100
11	TE_{112}	—	17 000	—	—	100
12	TM_{121}	1676	20 000	610	830	97
13	TM_{021}	—	17 000	—	—	100
14	TM_{030}	1776	28 000	2900	2900	90
15	TM_{112}	—	18 500	—	—	100
16	TE_{012}	—	27 000	—	—	100
17	TM_{031}	1954	18 500	700	700	96

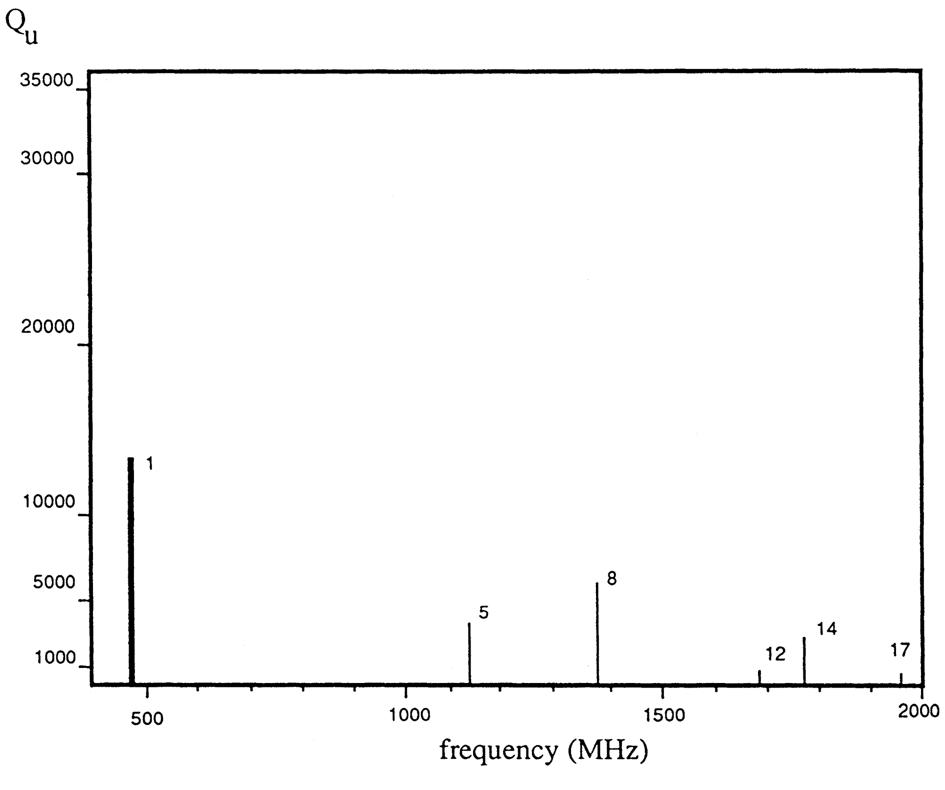

FIGURE 4 Mode spectrum of the pill-box cavity coupled to the suppressor prototype *wbs_rf2*.

The prototype *wbs_rf2* has a good effect also on other modes with higher resonant frequency; the global damping action is better than the one obtained with the first suppressor. The quality factor of the fundamental mode is still reduced by roughly ten percent, which we consider a satisfactory result.

6 CONCLUSION

A waveguide suppressor with adequate damping of the HOM spectrum has been designed and tested. Three different prototypes have been produced thus far. The first one operated at 3 GHz, the other two have been tested on a pill-box cavity with charactertistics similar to those of Elettra rf cavities. The last prototype, designed on the basis of the experience with the first two, guarantees quite good damping effects. The good performance on this technique is demonstrated by the following considerations:

- The fundamental mode quality factor is decreased by only 10%.
- Eleven out of sixteen HOMs taken into account are completely damped, three modes have a quality factor reduced to less than 10% of the undamped value and two modes have a quality factor reduced to less than 25% of the undamped value.

It is to be noted that these results were obtained without optimization of the coupling window.

Owing to the satisfactory results obtained with this model, investigations will be carried out in order to optimize its performance.

The final prototype of the HOM suppresor will then be coupled to the Elettra rf cavity prototype.

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